H.E.S.S. results on extended emission surrounding middle-aged pulsars

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for the H.E.S.S. Collaboration

1st Workshop on Gamma-ray Halos around Pulsars

01/12/20

H.E.S.S.

University of Zurich[UZH]

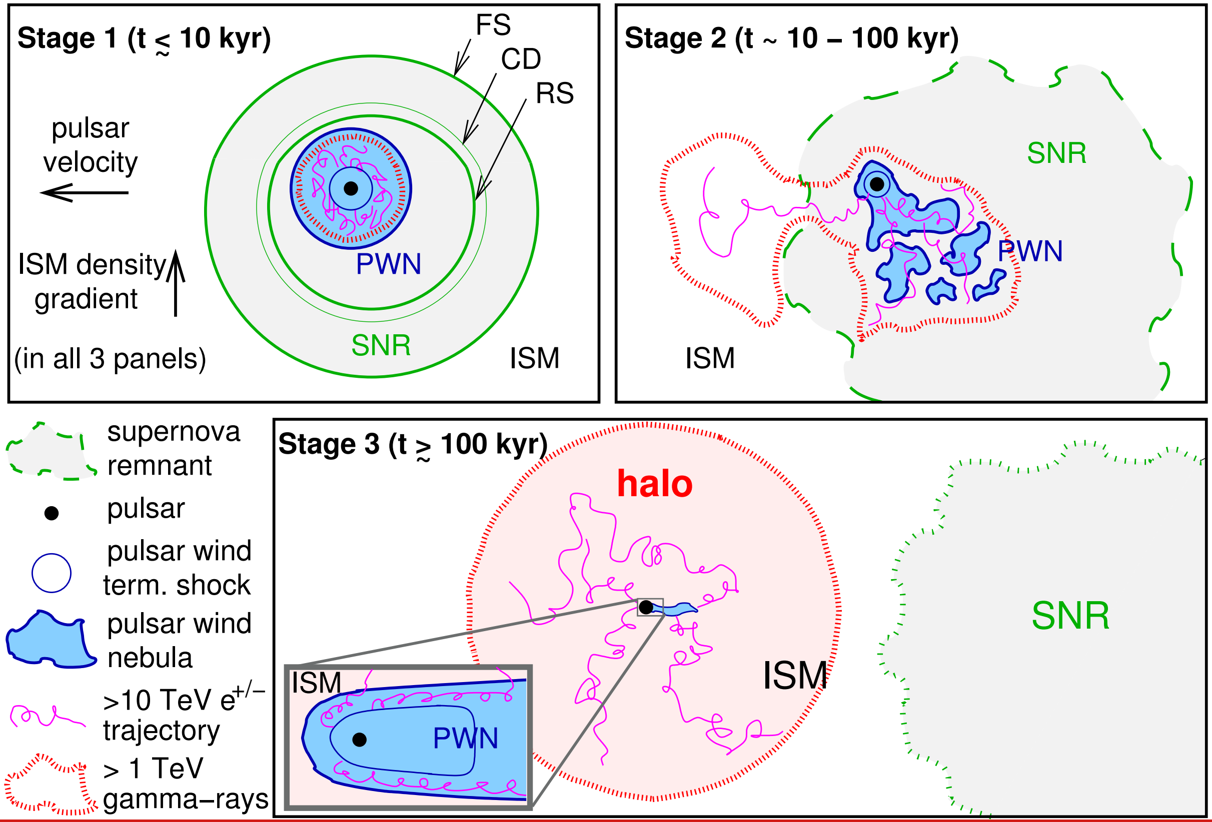
What are “middle-aged” pulsars?

- More related to evolutionary stage than fixed age range
- Roughly: few 10s kyr – 100s kyr

Giacinti et al, A&A 636, A113 (2020)

- System well past PWN reverberation phase
- Halo emission is far from plerion turbulence
- Complex – smooth evolutionary transitions → unclear catagorisation

- This talk: consider **Stage 2** and **Stage 3** systems



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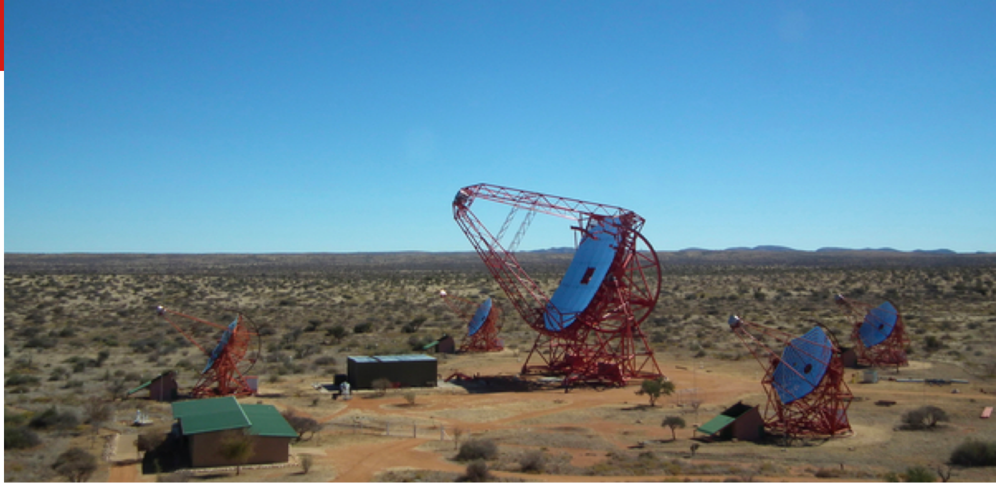
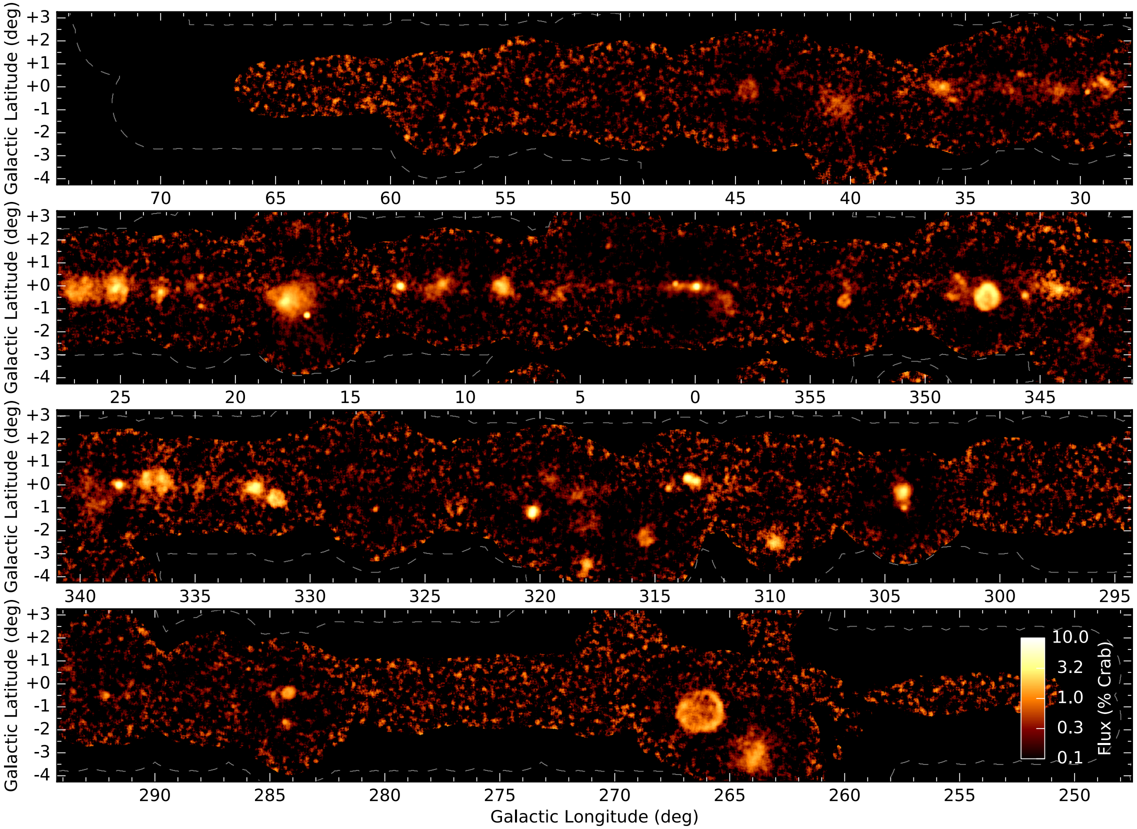


- Array of five IACTs in Kohmas Highlands, Namibia
- CT1-4 108m^2 mirror area operational since 2004
- CT5 614m^2 mirror area, constructed in 2012
- Field-of-view: 5º (CT1-4)
- 50 GeV – 50 TeV range
  (c.f. HAWC ~ 1 – 100 TeV)
- ~0.1º angular resolution
  (c.f. HAWC ~0.2º - 1º)



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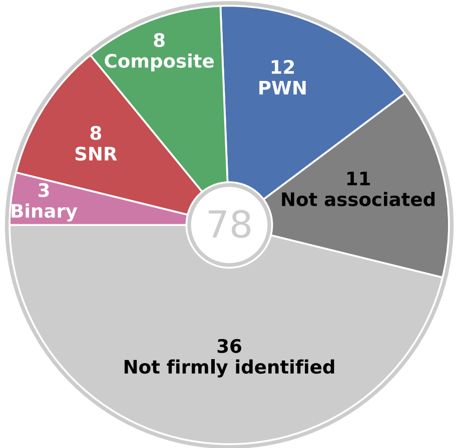
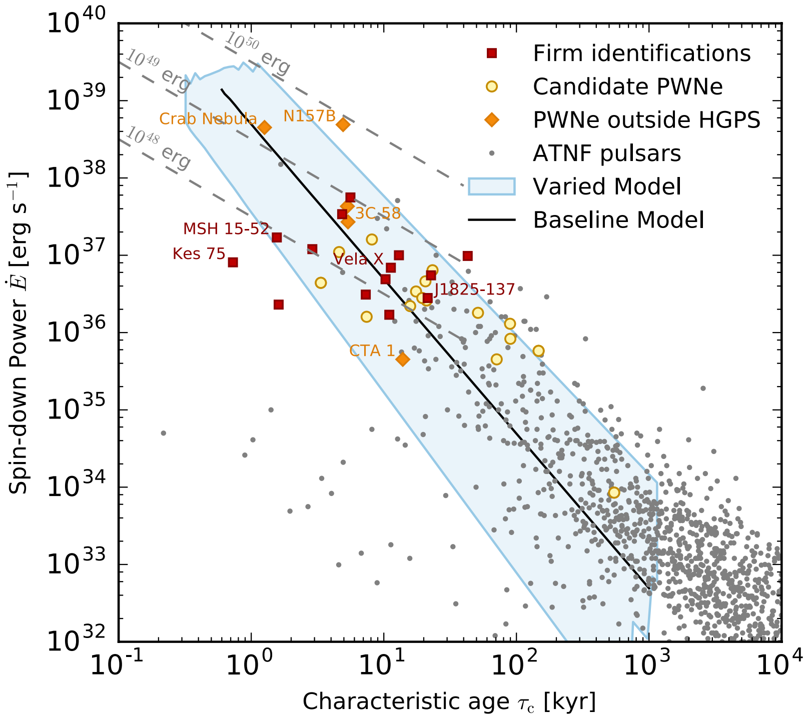
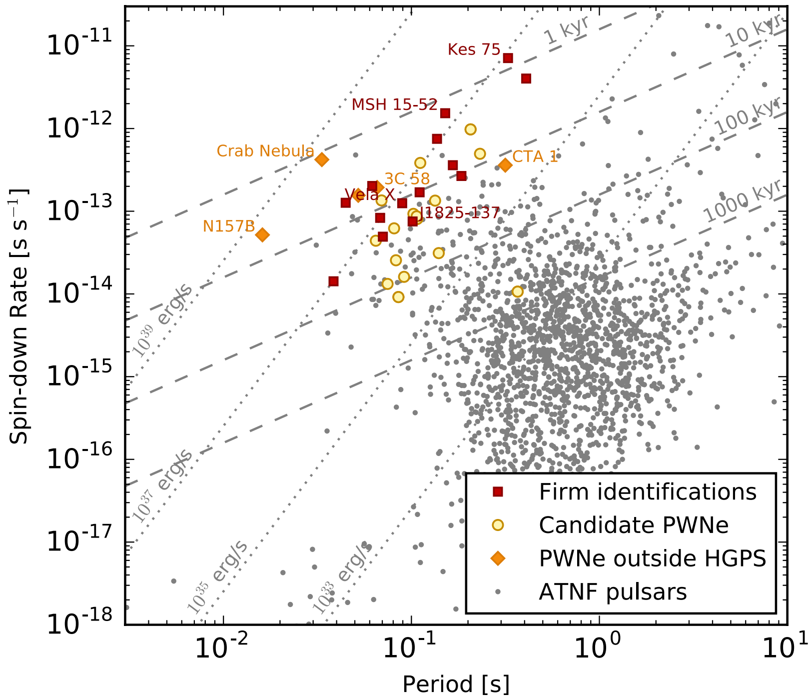
H.E.S.S. Galactic Plane Survey: PWN population study

- 12 PWN, 8 composite (+5 outside HGPS)
- 36 confused + 11 UNID → more PWNe?
- 20 candidates; tip of the Iceberg?



H.E.S.S. Collaboration, A&A 612, (2018) A2

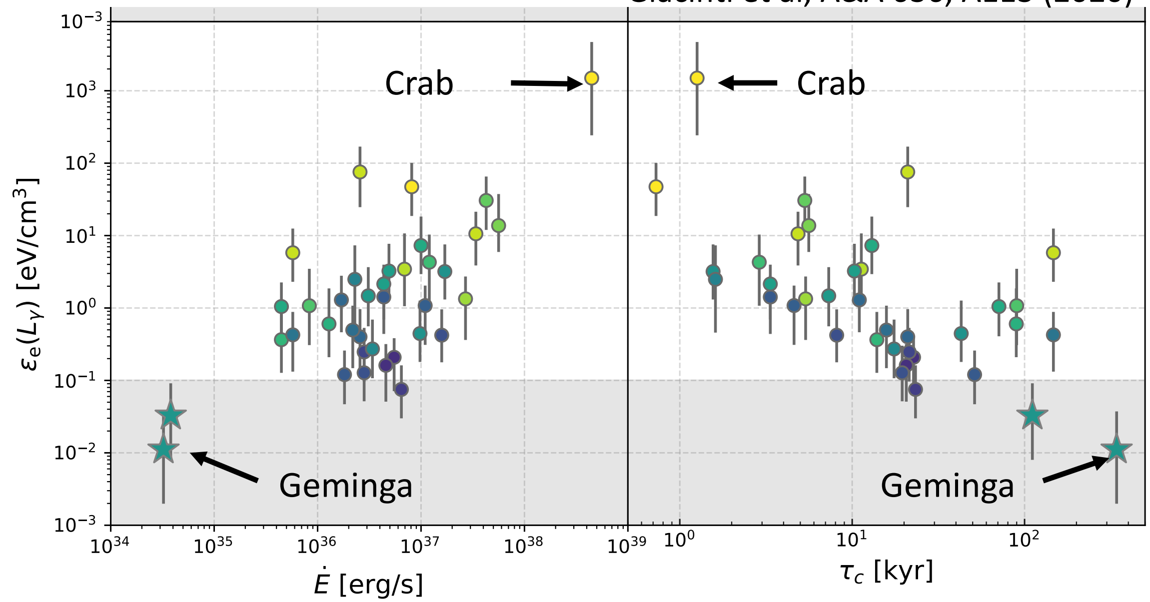




Known PWN / halo population

- Halos as region with energy density far below ISM levels ~0.1 eV/cm-3
- What about other halos?

Giacinti et al, A&A 636, A113 (2020)



How to distinguish from PWN?

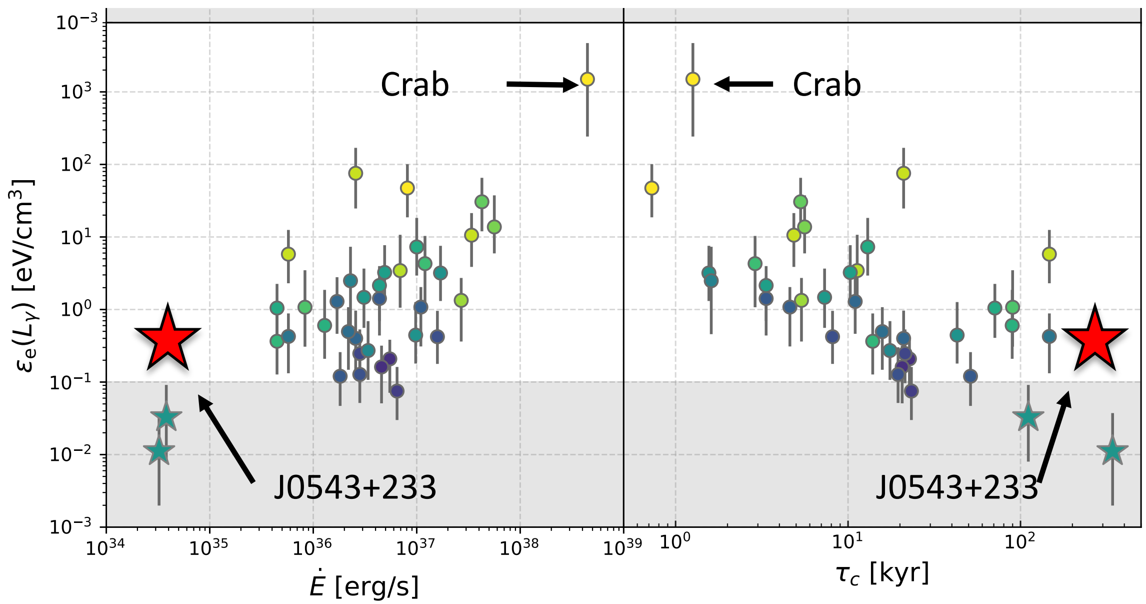
Non-thermal emission beyond PWN e.g. Sudoh et al, PhysRev D 100, (2019) 043016

Energy density in electrons, pulsar does not dominate dynamics e.g. Giacinti et al, arXiv:1907.12121

→ Discussion tomorrow

Known PWN / halo population

- Halos as region with energy density far below ISM levels ~0.1 eVcm^{-3}
- What about other halos?
- HAWC J0543+233 around PSR B0540+23 ($\dot{E}$ = 4.1 ×10^{34} erg s^{-1}, distance= 1.56 kpc, τ_c = 253 kyr)
- TeV size ~0.5º (*too small*?)
- Energy density = 0.6 eVcm^{-3}



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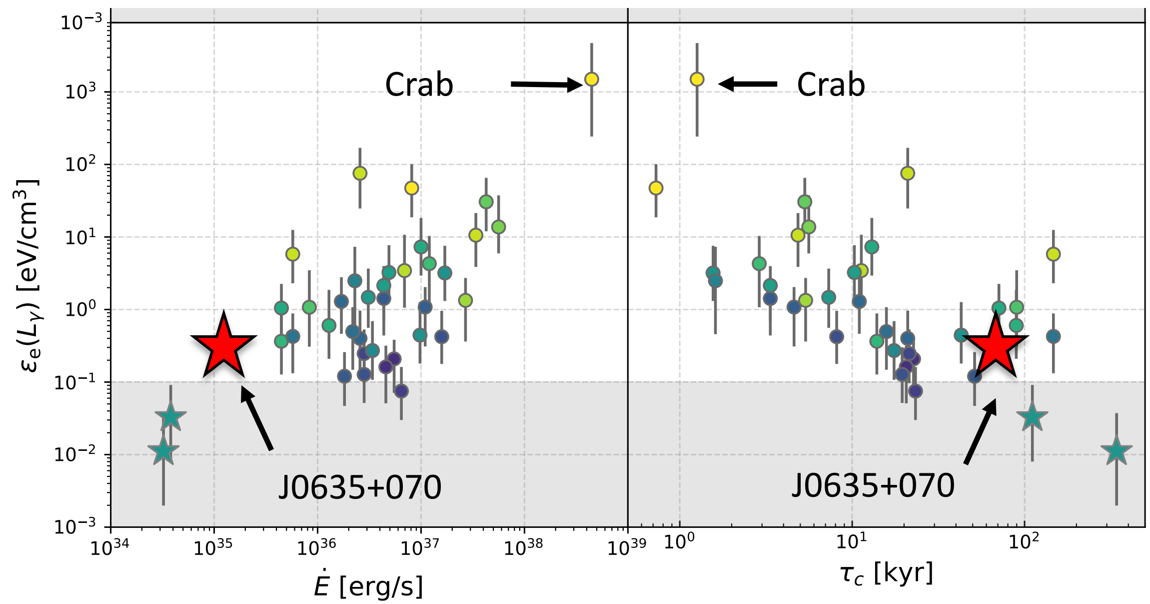
→ Discussion tomorrow

Known PWN / halo population

- Halos as region with energy density far below ISM levels ~0.1 eVcm^{-3}
- What about other halos?
- HAWC J0635+070 around PSR J0633+0632 ($\dot{E}$ = 1.2 ×10^{35} erg s^{-1}, distance= 1.35 kpc, τ_c = 59 kyr)
- TeV size ~0.65° ± 0.18°
- Energy density = 0.3 eVcm^{-3}



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→ Discussion tomorrow

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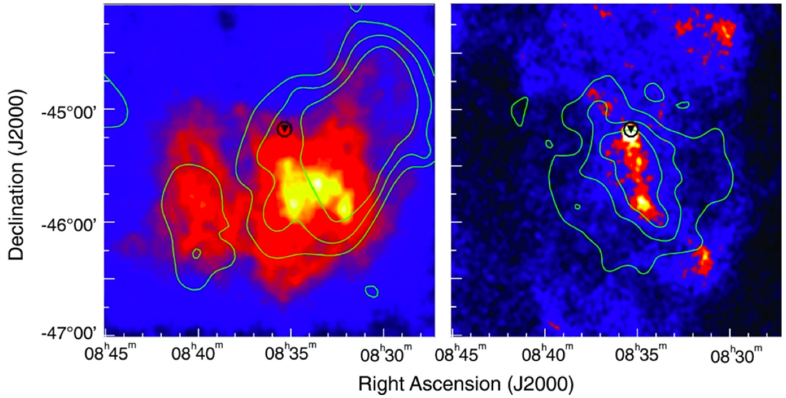
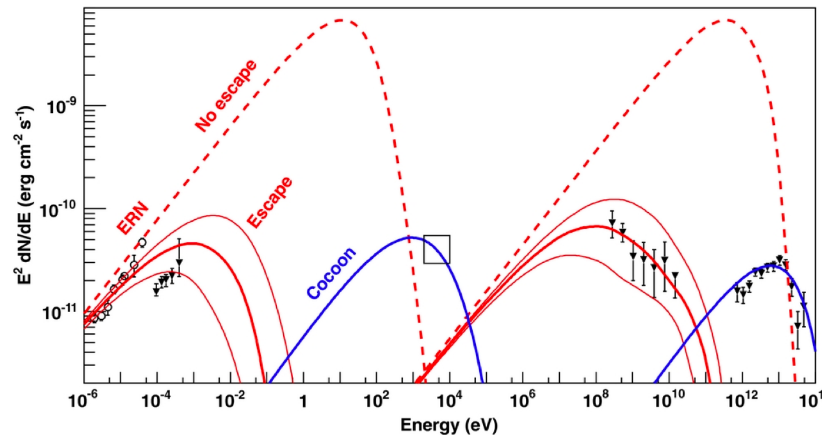
Vela X

Not a halo!

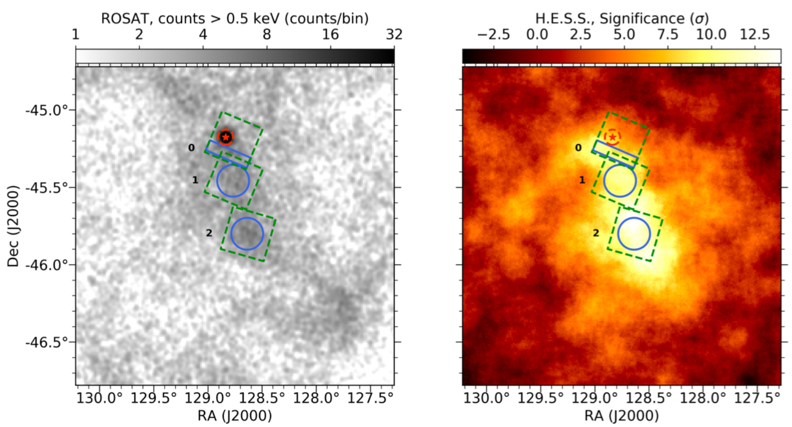
Hinton et al. ApJLett 743 (2011) L7

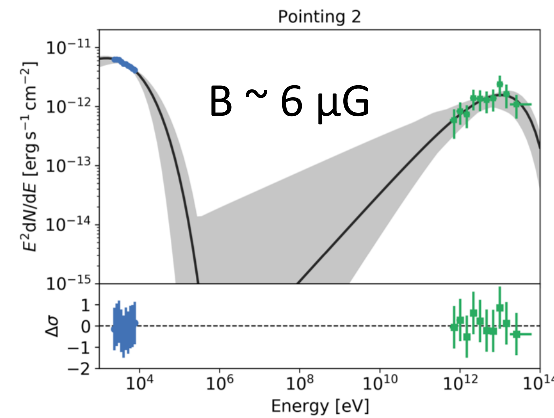


- Age = 11.3 kyr, log(Edot) = 36.84 erg/s, Distance = 0.28 kpc,
- R: radio = 12.2 pc, X-ray = 3.08 pc, TeV = 2.9 pc
- Escaped particles in extended radio nebula (ERN)
- Indications for advective transport



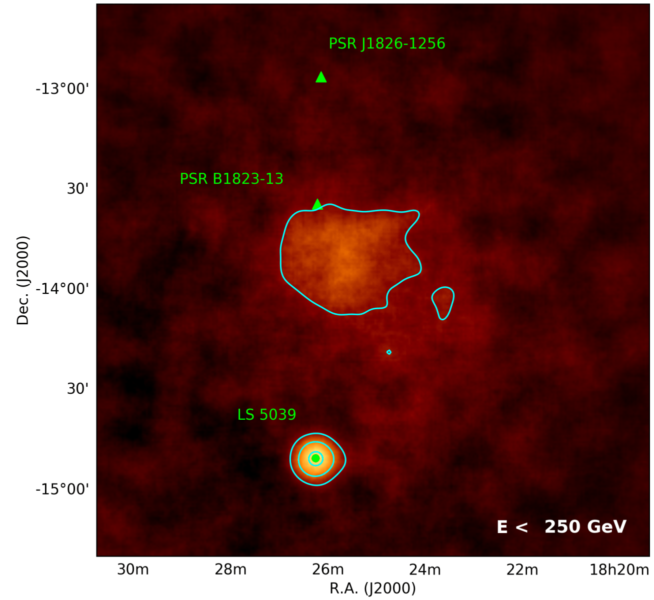
H.E.S.S. Collaboration, A&A 627, (2019) A100





HESS J1825-137

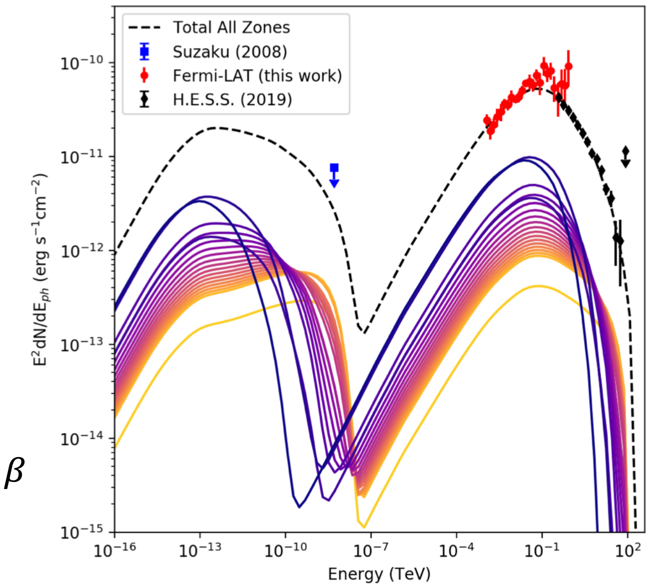
- Age = 21.4 kyr, log(Edot) = 36.45 erg/s, Distance = 3.9 kpc,
- R: radio = 0.4? pc, X-ray = 9.1 pc, TeV = 50 pc

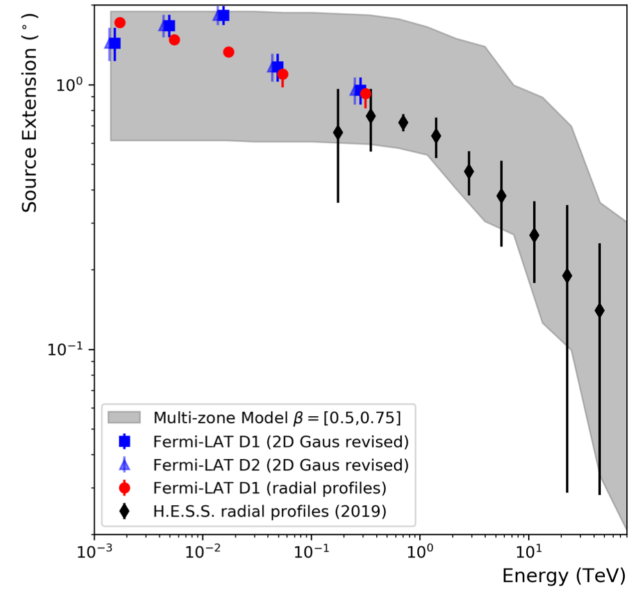


H.E.S.S. Collaboration, A&A 621, (2019) A116

- Strong energy dependent morphology
- Bright at E > 100 TeV
- Indications for advective particle transport
- See poster by Principe et al.

Principe et al. A&A 640, A76 (2020)





$$v(r,t) = v_0 \left(\frac{r}{r_{max}}\right)^{\beta} \left(\frac{t}{T}\right)^{-\beta}$$

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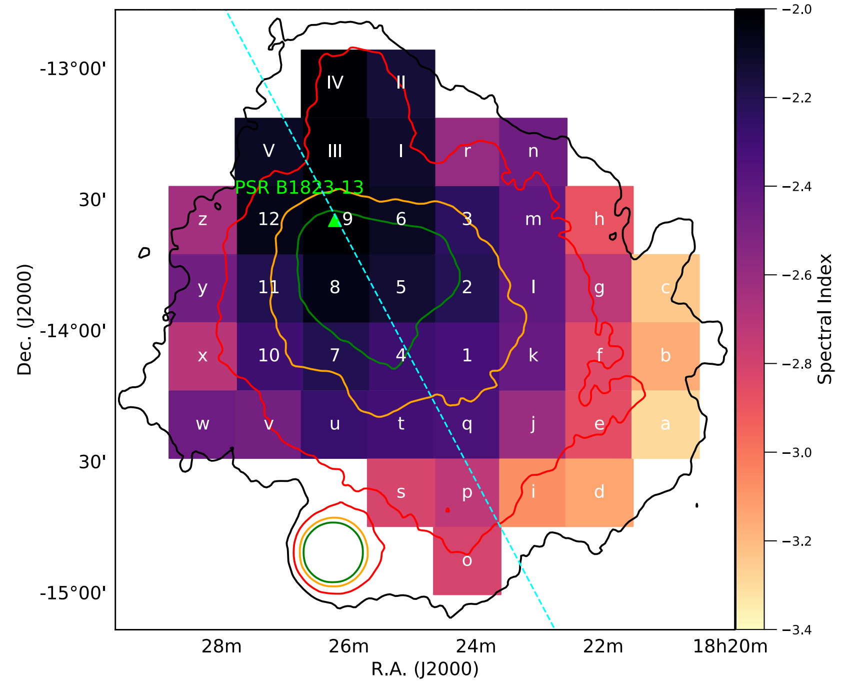
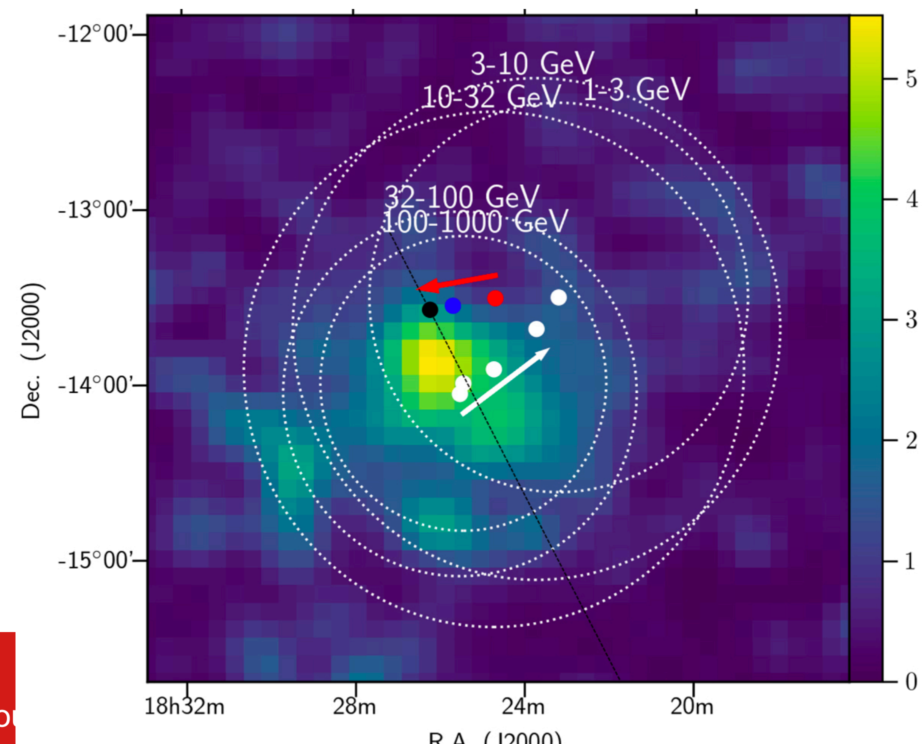
HESS J1825-137

Partly a halo?!

- PWN – halo hybrid?
- Energy density ~0.17 eV/cm-3 over whole nebula
- A lot of variation between regions however
- Drift in best fit position with energy corresponding to pulsar proper motion trajectory
- Lower energy emission from older electrons emitted at earlier times

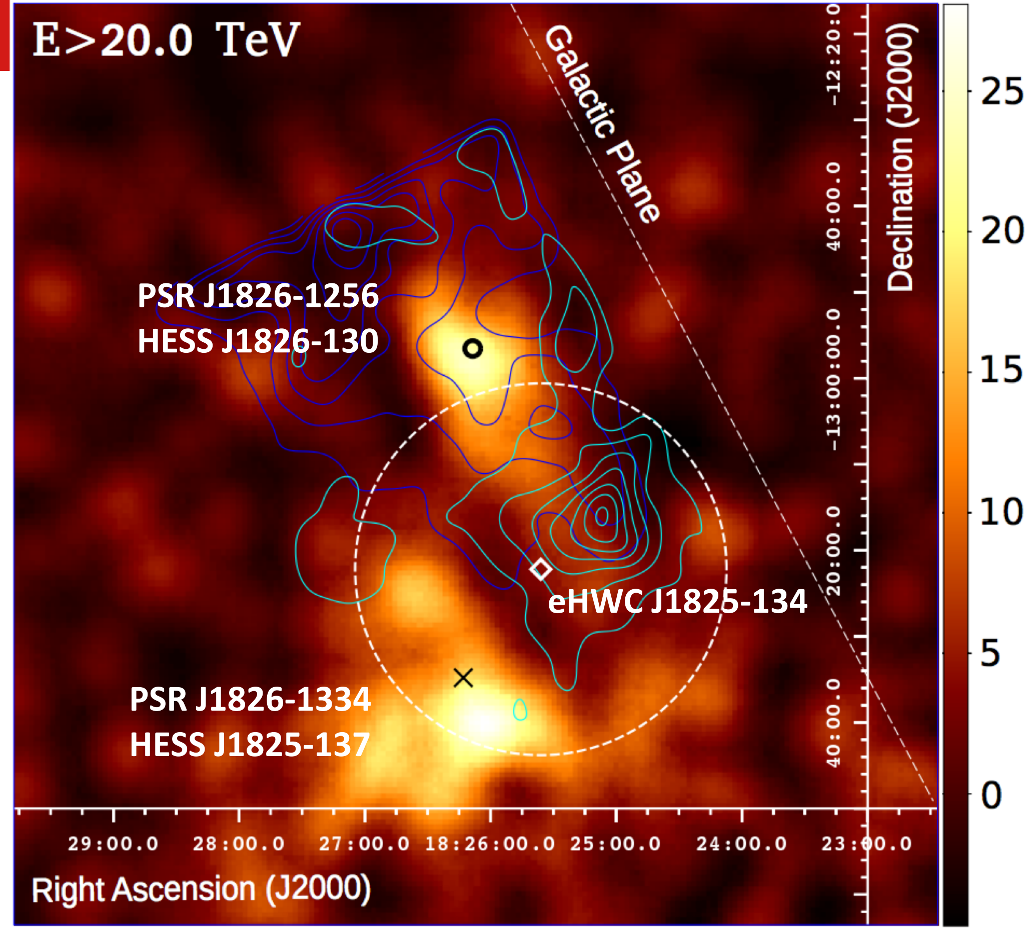




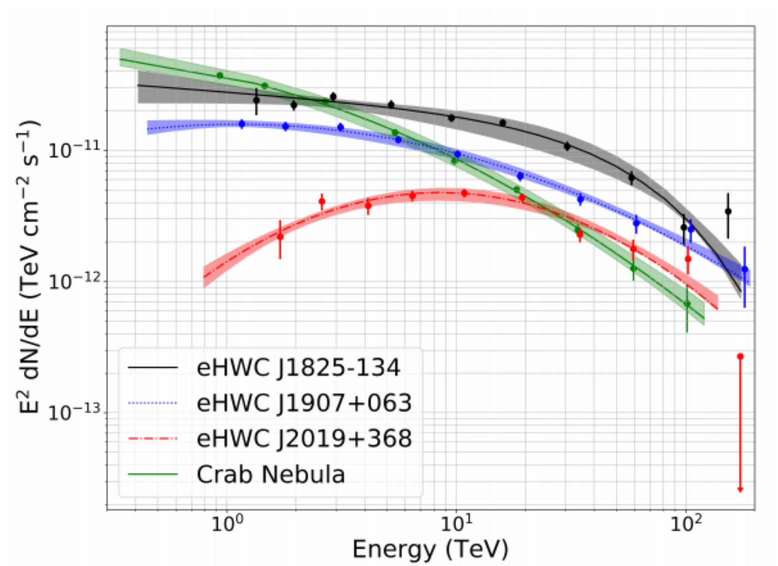
HESS J1826-130

Not a halo!

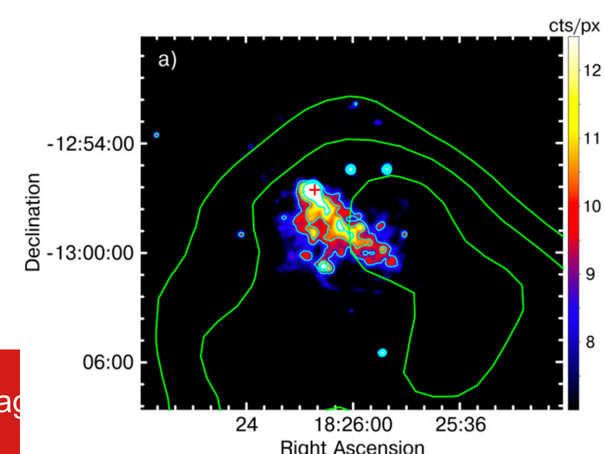
- Age = 14.4 kyr, log(Edot) = 36.56 erg/s, Distance = 1.2 – 3.5 kpc,
- R: radio = ? pc, X-ray = 6’x2’, TeV = 0.21°
- Emission from region >100 TeV



HESS Collaboration, A&A (2020) arXiv:2010.13101



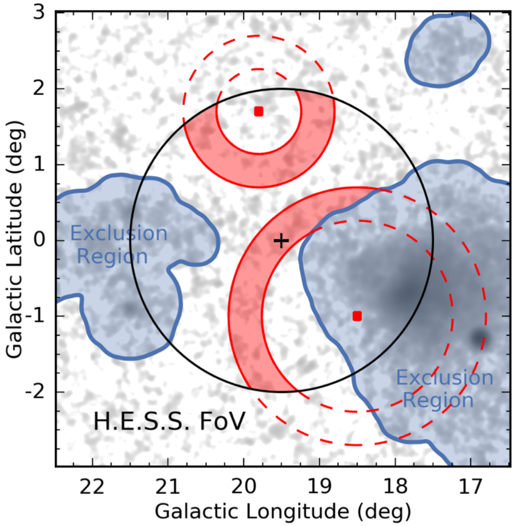
HAWC Collaboration, PRL 124, 021102 (2020)



Duvidovich et al, A&A 623 (2019) A115

HAWC - H.E.S.S. analysis comparison study

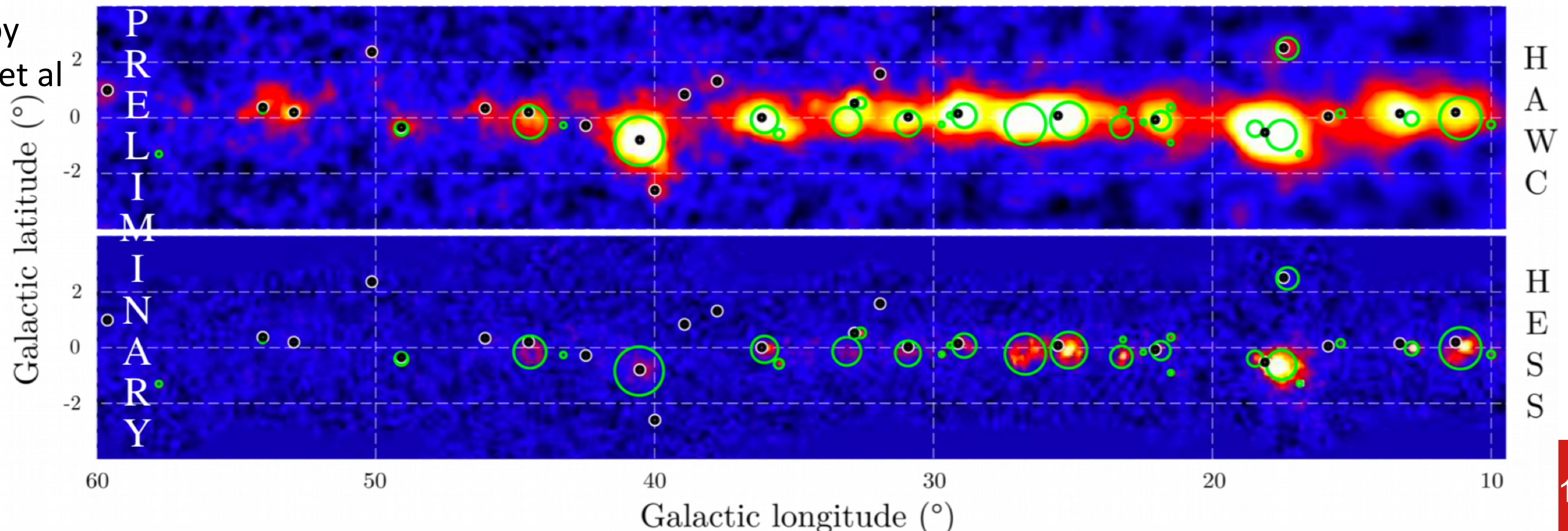
- Recent dedicated effort in understanding analysis differences
- Tested in Galactic plane
- Ring Background:
  fixed offset from test position, estimate from data outside exclusion regions
- Field-of-View Background:
  use acceptance map for background estimation, assuming radial symmetry



H.E.S.S. Collaboration, A&A 612, (2018) A1

Jardin-Blicq et al ICRC 2019

See poster by Jardin-Blicq et al on 3HWC J1928+178



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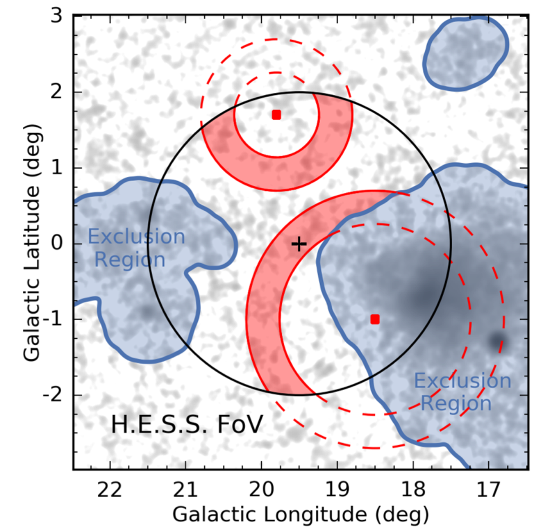

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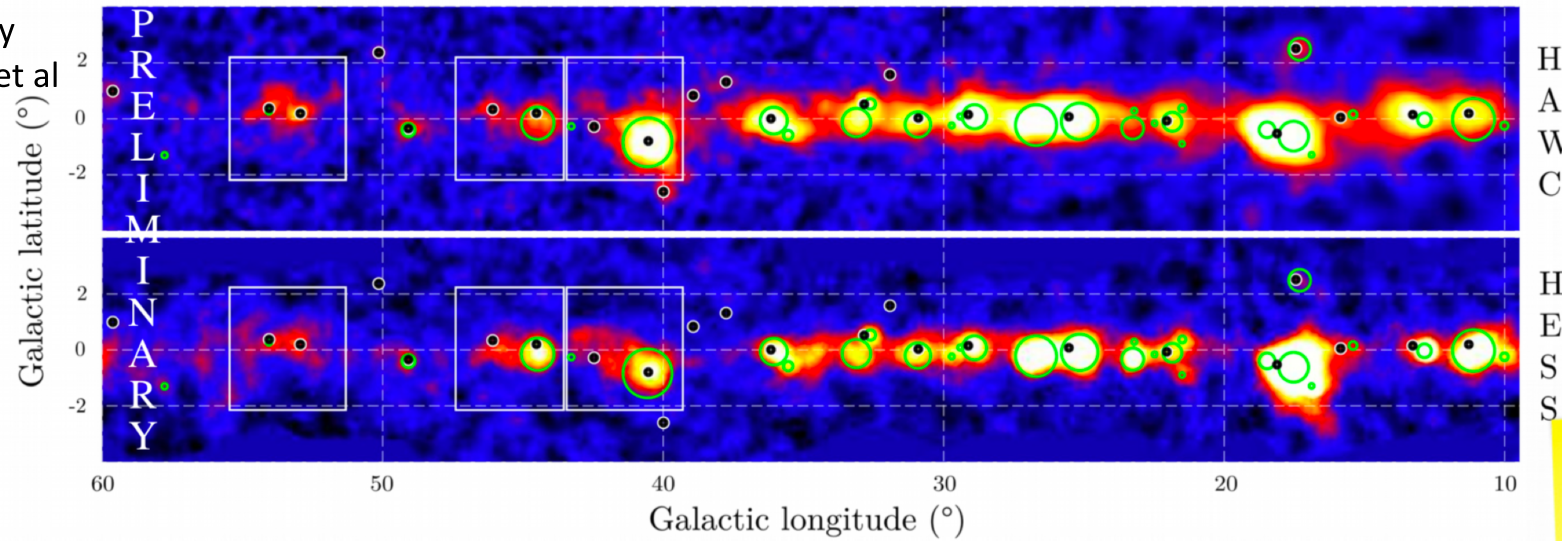
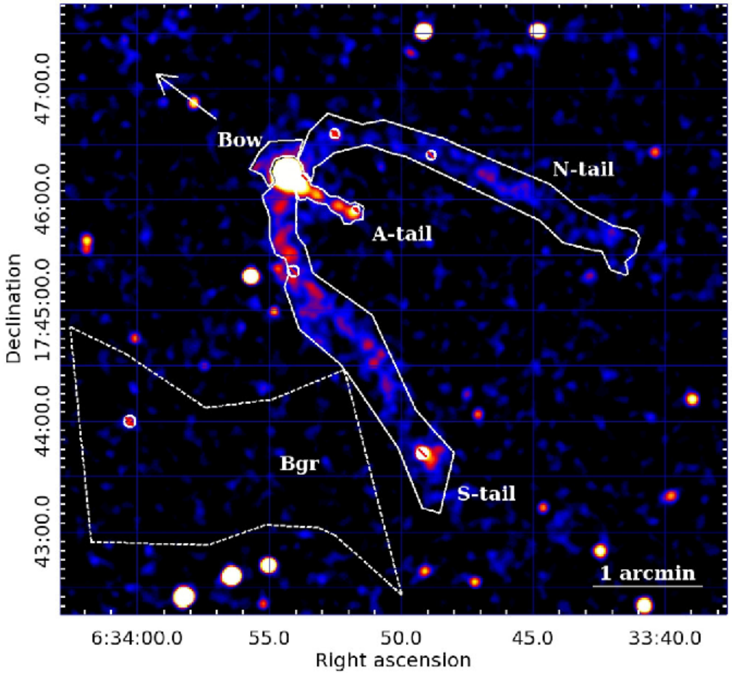


The Geminga Pulsar



Posselt et al, ApJ 835, 66 (2017)

- Radio quiet pulsar: strong gamma-ray and weak radio pulsed emission
- Gamma-ray pulsar detected (EGRET, MAGIC)
- Age = 342 kyr, log(Edot) = 34.51 erg/s, Distance = 0.25 kpc,
- R: radio = 0.01 pc, X-ray = 0.15 pc, TeV = 100 pc

- Pulsars are copious lepton producers → nearby pulsars could help explain positron excess

- Previous searches for extended emission in gamma-ray and radio
- X-ray and Radio PWN confirmed (on arcsecond – arcminute scales)
- Detection of extended gamma-ray emission around Geminga found by Milagro & HAWC
- Challenging for IACTs due to large scale emission

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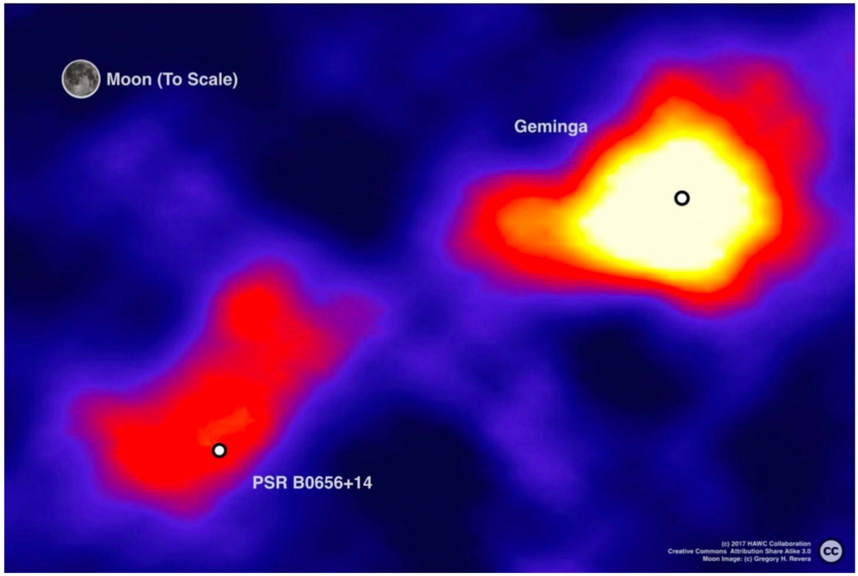
HAWC detection of extended TeV emission

- HAWC confirms Milagro excess
- Extended emission on ~2° scale

- Low diffusion coefficient inferred by HAWC from radial profile of emission
- For escaped particles in the ISM – surprisingly slow
- Would imply Geminga is not local positron source if representative of intervening ISM

- Cool too quickly to reach Earth

- Halo rather than PWN?



RA-Dec, HAWC collaboration 2017

Definitely a halo!

Side note:
PWN are expected to have slow diffusion. The surprise is that diffusion is slow in a region supposedly representative of the ISM.

Diffusion Modelling (S. Caroff)

- Developing model for diffusion with a more accurate energy loss description
- Difference to HAWC approximation becomes significant over HESS energy range
- Model using HAWC derived diffusion coefficient
  → emission radius > HESS FoV

- Approximations used in
  HAWC collaboration, Science 358, 911-914 (2017)

$$f_d = \frac{1.22}{\pi^{3/2} r_d (d + 0.06 r_d)} exp(-d^2/r_d^2)$$

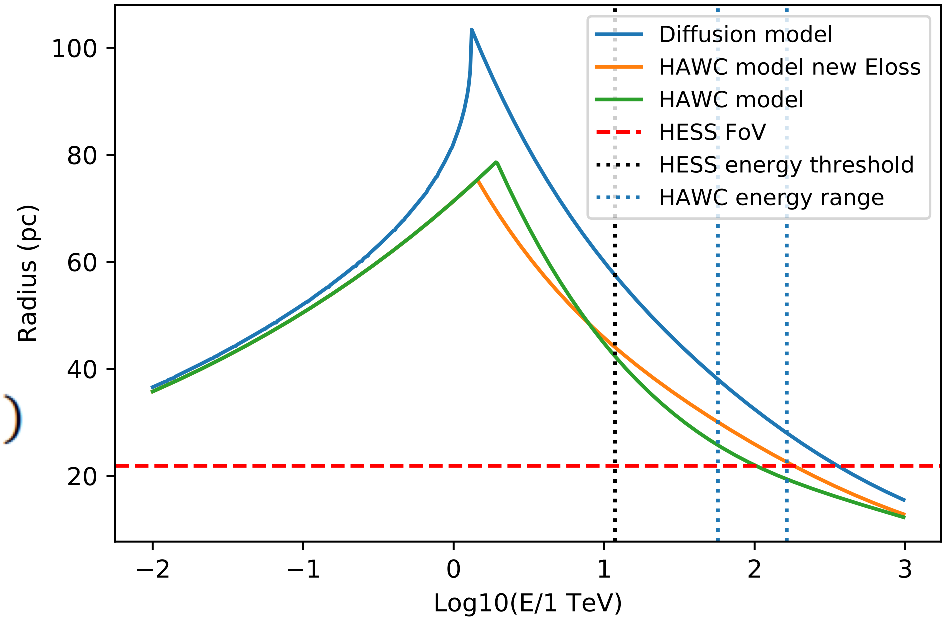
$$r_d = 2\sqrt{D(E_e) t_E}$$

Semi-analytical solution
di Mauro et al, PRD 100, 123015 (2019)

$$\mathcal{N}_e(E, \mathbf{r}, t) = \int_0^t dt_0 \frac{b(E_s(t_0))}{b(E)} \frac{1}{(\pi \lambda^2(t_0, t, E))^{\frac{3}{2}}} \times \times \exp\left(-\frac{|\mathbf{r} - \mathbf{r_s}|^2}{\lambda(t_0, t, E)^2}\right) Q(E_s(t_0)), \quad (16)$$

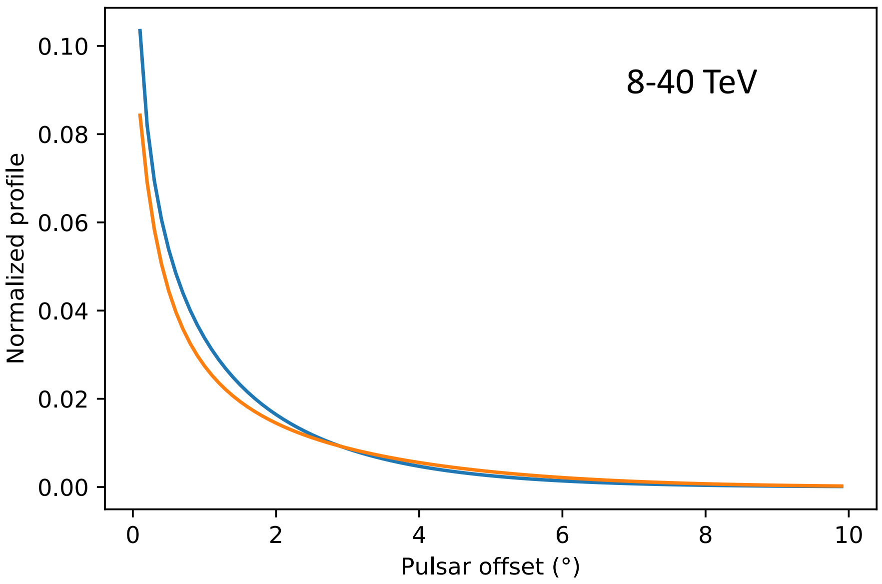
Diffusion radius:

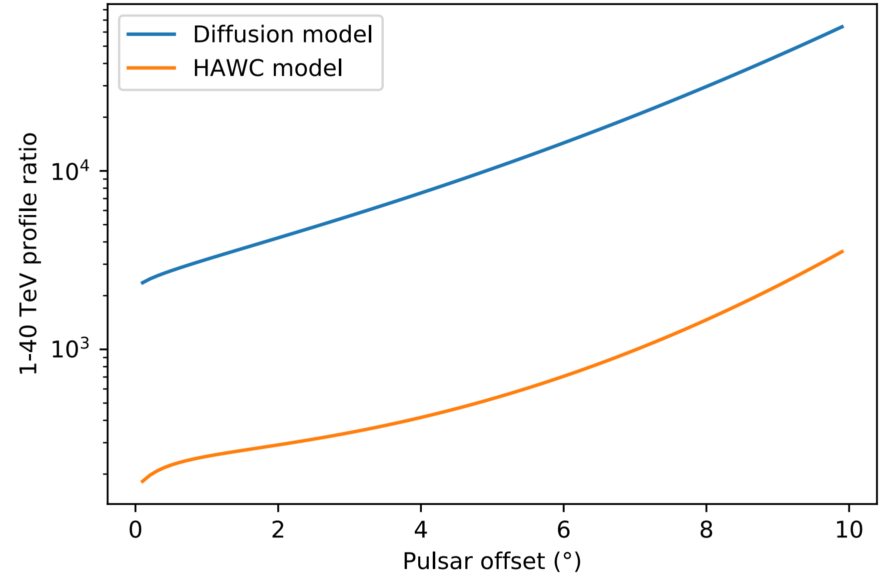
$$\lambda^2 = \lambda^2(E, E_s) \equiv 4 \int_E^{E_s} dE' \frac{D(E')}{b(E')}, \quad (14)$$



Model comparison

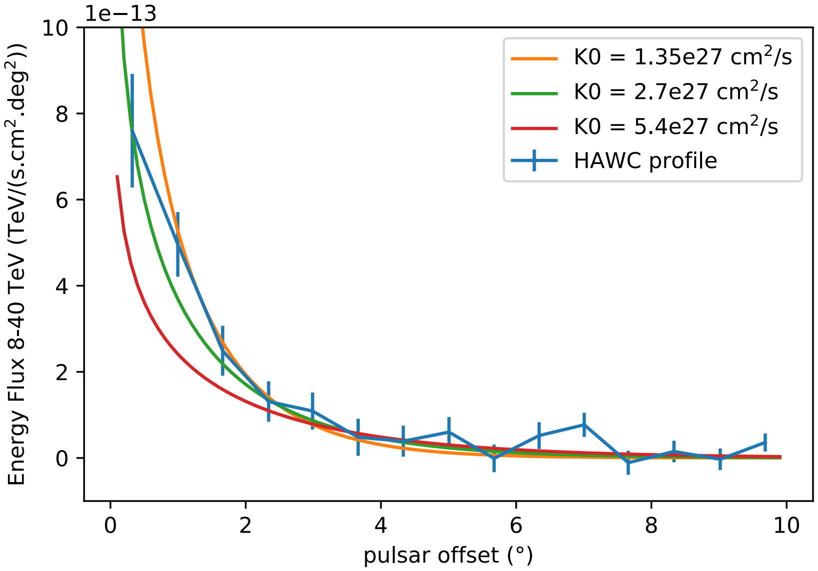
- Different models lead to minor differences in shape
- Give similar results for profile within a single energy bin
- Comparing over a wider energy range, models can lead to significant influence in normalisation
- Full diffusion model mandatory to simultaneously fit multiple energy bins

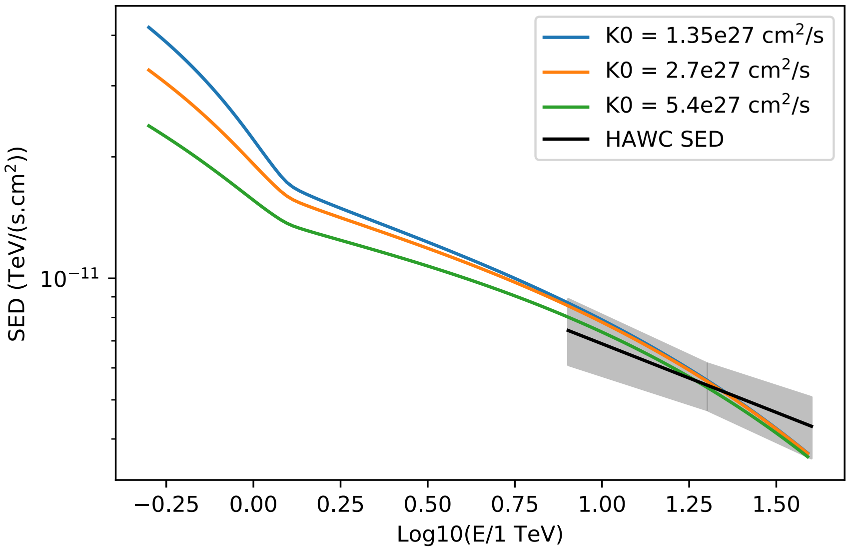




Parameter influence on model: Diffusion Coefficient

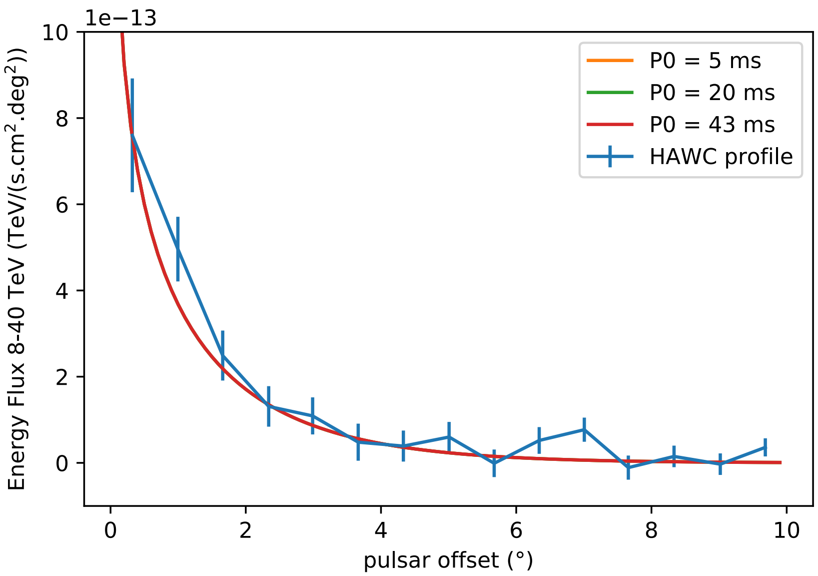
- Variation in K0 does not significantly affect spectral shape

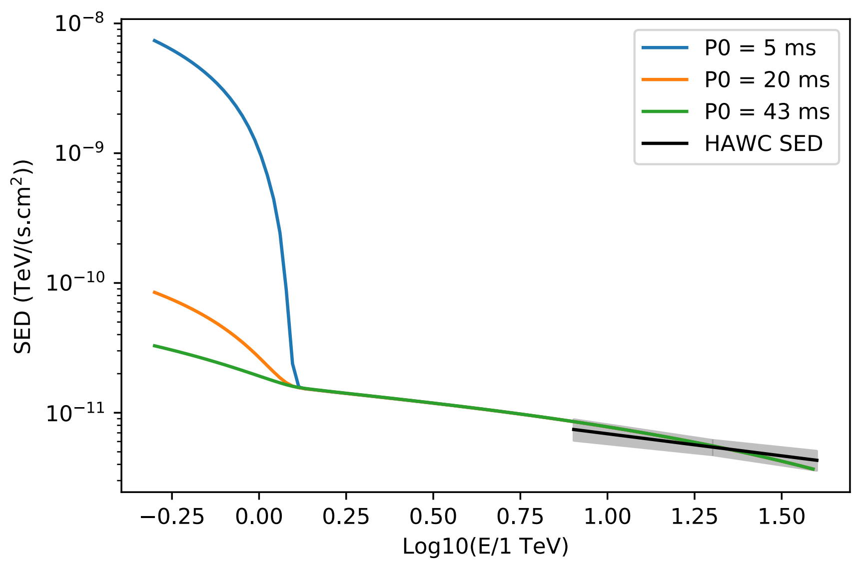




Parameter influence on model: Initial period

- Initial period does not affect high energies > 1.5 TeV
- Can create an energy break within HESS energy range due to relic electrons produced at pulsar birth
- Break energy depends on pulsar age and electron cooling

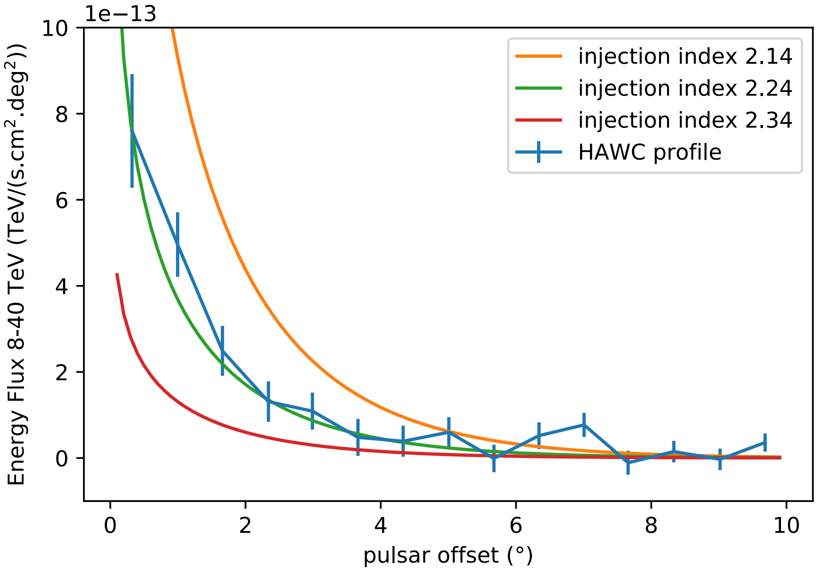


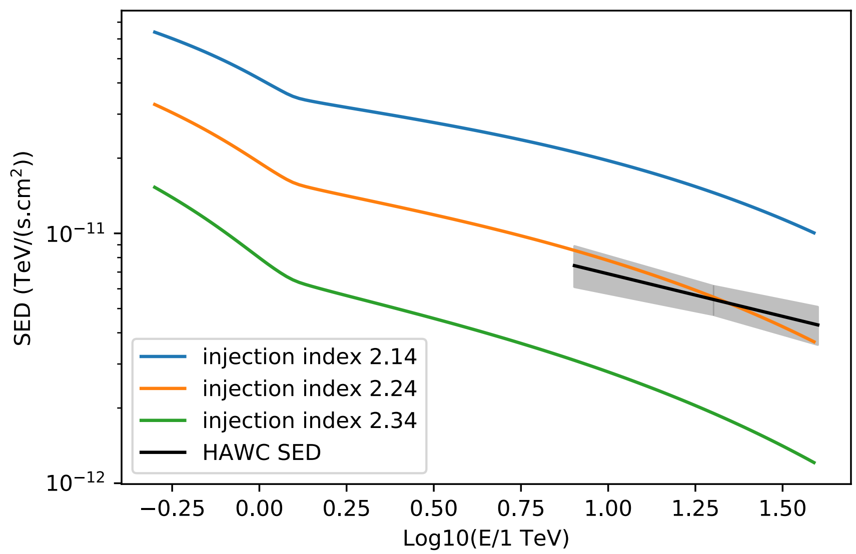


Potential influence of proper motion under study

Parameter influence on model: Injection index

- Injection index affects profile normalisation, SED shape & normalisation
- Pivot energy of injection spectrum is at 1TeV





H.E.S.S. Observations of Geminga 2006-2008

Time Period	Exposure	Zenith angle
Nov 2006	7.7 hours	42.2º
Jan-Feb 2008	6.5 hours	42.0º

- Data taken in 2006 and 2008
- Observations with H.E.S.S. I telescopes
- 0.5º and 0.7º wobble offset
- 14.2 hours total livetime

- No significant excess seen at the time

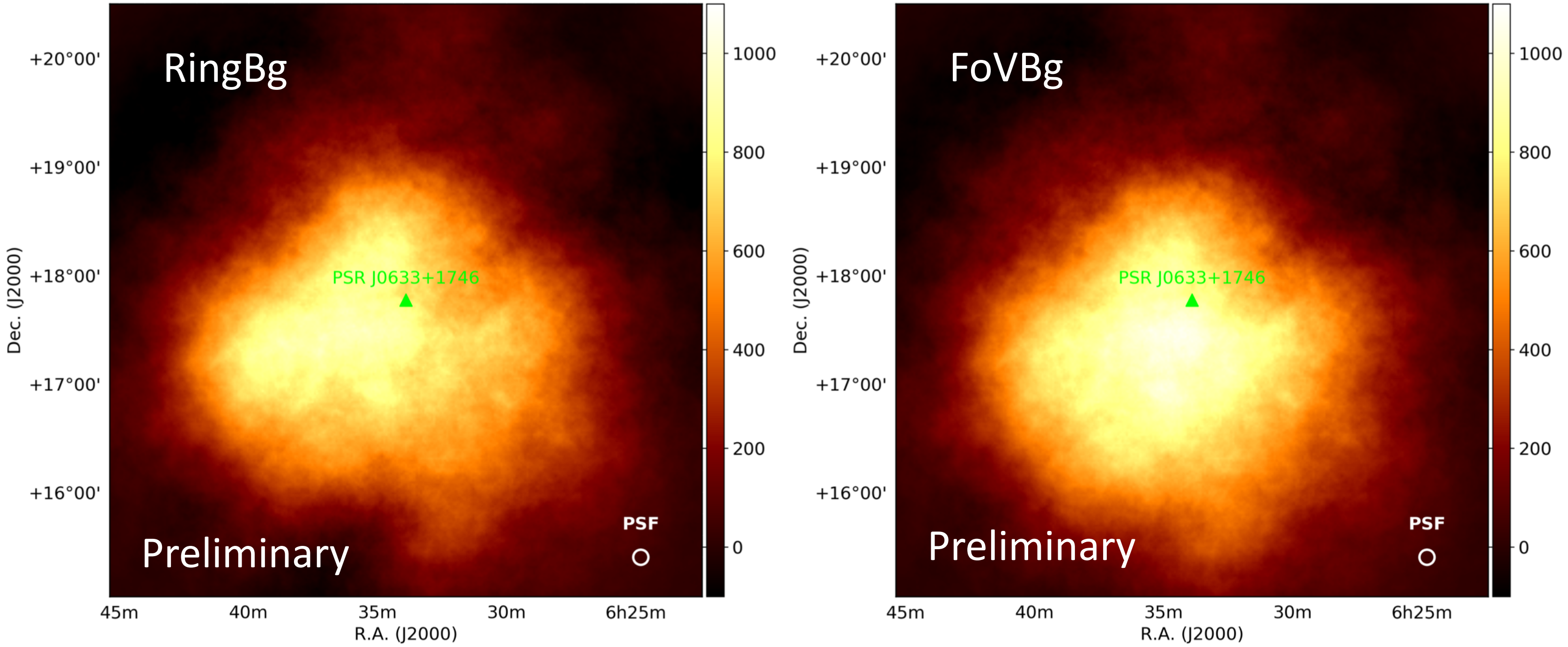
- From HAWC spectra, detection should be possible in ~10 hours

- Revisit data applying lessons learnt from HAWC-H.E.S.S. analysis comparison study

- H.E.S.S. analysis with S. Caroff (LPNHE)

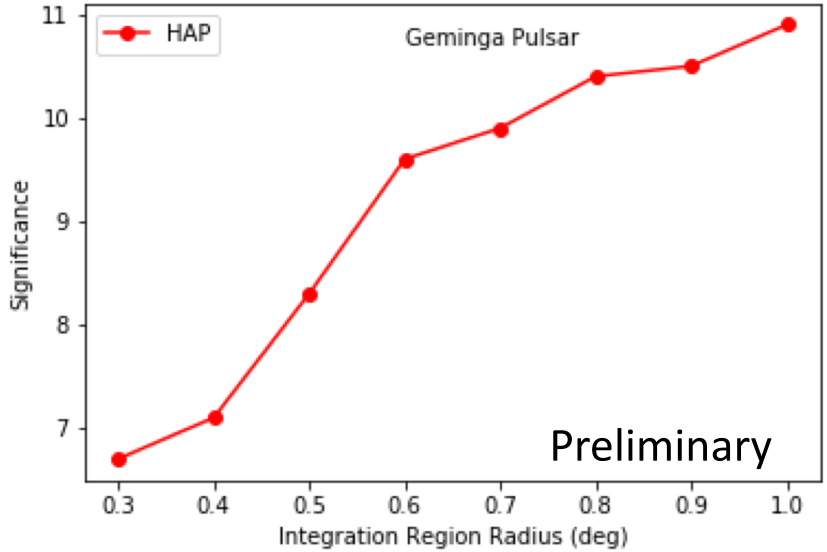
H.E.S.S. detection of extended gamma-ray emission
(TeVPA 2019)

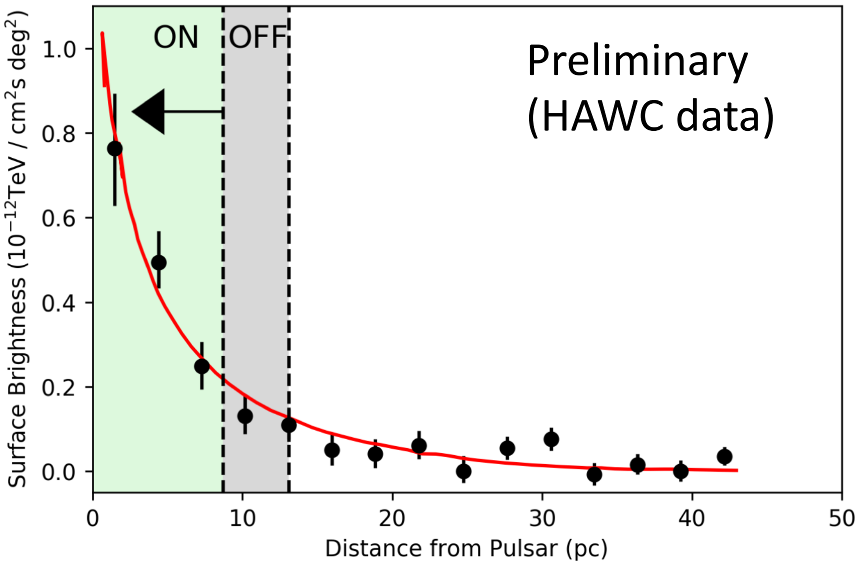
- Ring background: 10.9 sigma within 1º of pulsar (background estimation includes source events)
- Field of View Background – normalise to region outside exclusions.
- Consistent morphology, different normalisation between background methods
- However, background estimation methods may bias apparent morphology



Integration region and angular scale

- Significance increases with increasing radius
- Curve does not flatten
- True extent > 1º radius
- Compared to previous searches with IACTs, H.E.S.S. now probes much larger angular scale
- Differential measurements – part of significant emission used to estimate background.





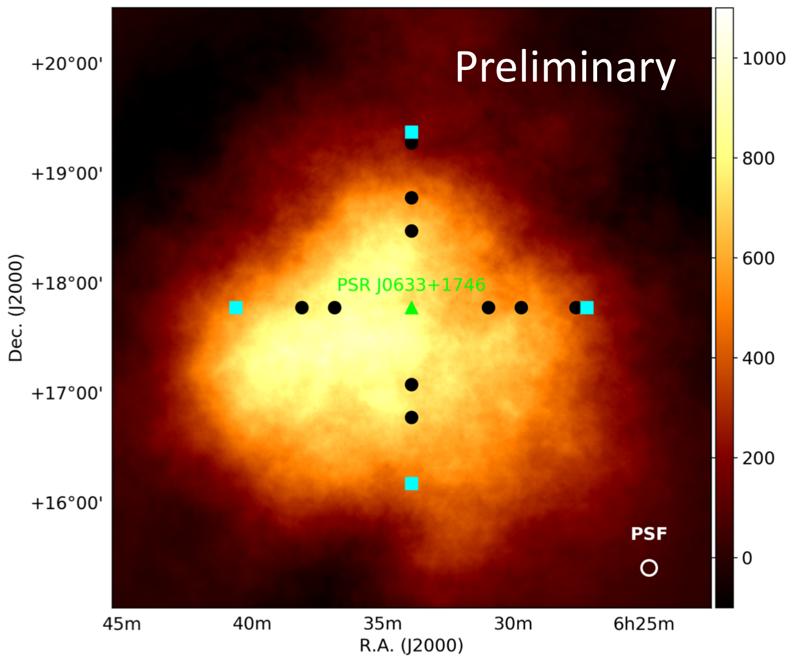
See also HAWC collaboration, Science 358, 911-914 (2017)

Observations in 2019

- Another 30 hours of observations taken at large offset (1.6º wobble)
- cf. 0.5º - 0.7º usual "wobble"

- Analyse with OnOff background method; extragalactic runs as OFF data

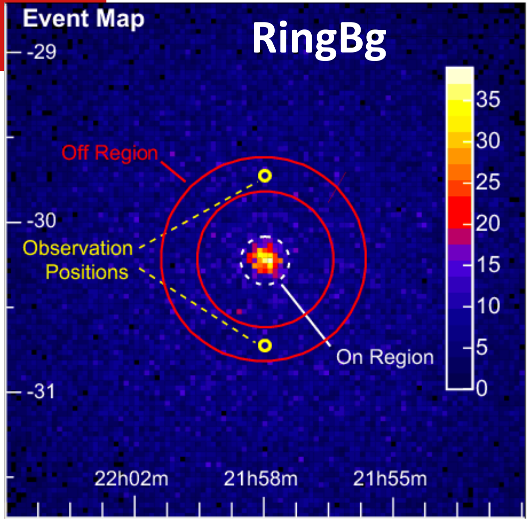
- Challenges – good run matching selection, background normalisation, acceptance…

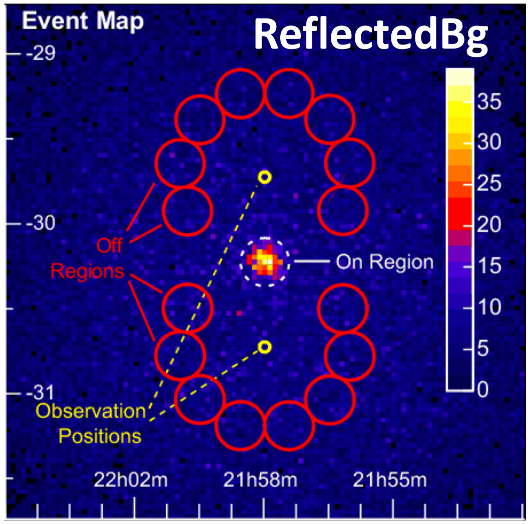


Black circles – 2006-2008 observation positions
Cyan squares – 2019 observation positions

Background Estimation Methods

- Several background methods used by IACTs
- Which one is most suitable?

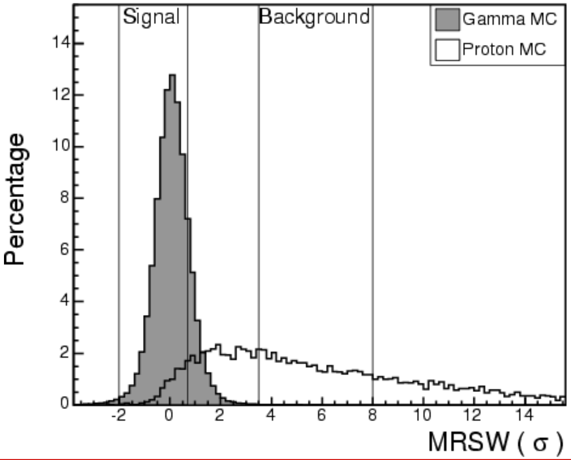




Berge et al, A&A 466, 1219-1229 (2007)

	ring	*reflected-region*	*template*	*field-of-view*	*ON/OFF*
Contemporaneous	Y	Y	Y	Y	N
FoV position	N	Y	Y	N	Y
Sky position	N	N	Y	N	N
Event statistics	Y	Y[5]	Y	Y	N
Event type	Y	Y	N	Y	Y

TemplateBg



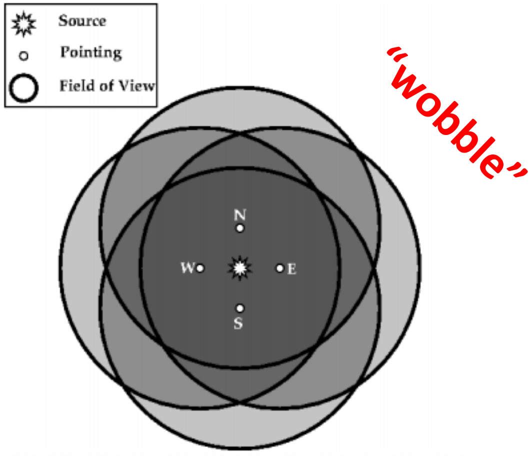
- Source detection? Ring
- Source spectra? Reflected
- Extended source spectra? ON/OFF
- Morphology? Field-of-view

Observation Strategies

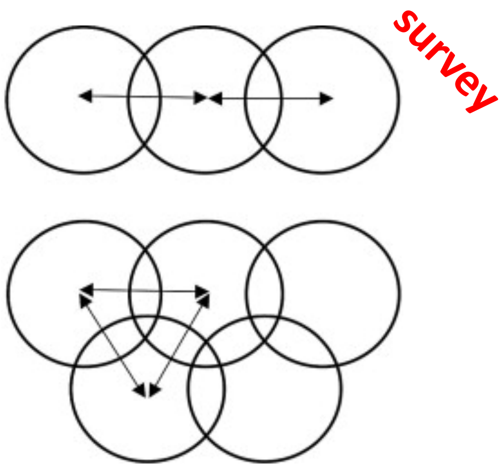
- WCD instruments – scan whole sky (15% sky field-of-view)
- IACT – pointed facilities (3º - 5º field-of-view)

- Need to be offset from source due to radial acceptance
- Observe in “wobble” mode?
- Grid of observation positions (survey)?
- Drift-scan: fixed position and let sky move through camera?

- Analysis can be complex



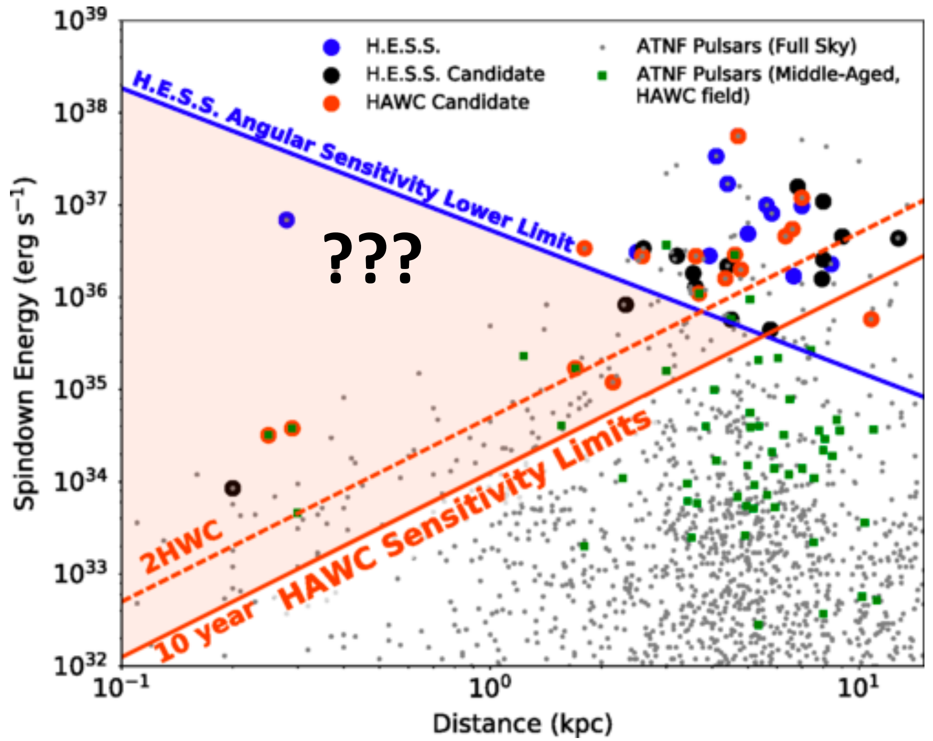
Kieda ICRC arxiv:1110.5974



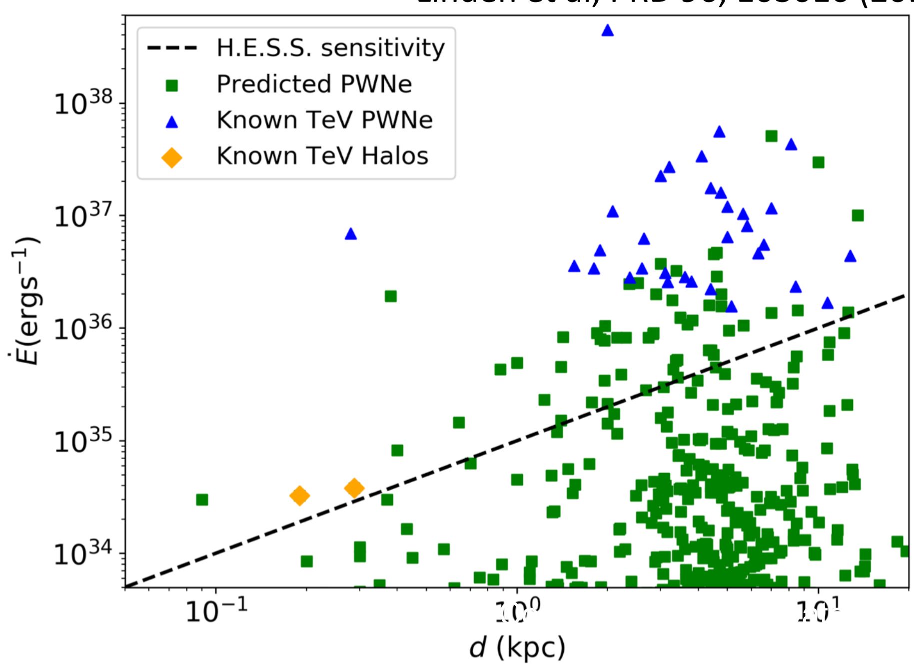
Dubus et al. Astropart. Phys. 43, 317-330 (2013)

H.E.S.S. Angular Sensitivity

- Model $\theta_{TeV} = \left(\frac{d_G}{d_{psr}}\right)\theta_G$ based on Geminga with 2º size?
- Impose a limit of 0.6º (c.f. HGPS)
- H.E.S.S. sensitivity is **flux** limited
- For large sizes, cannot measure **size** (limited Field of View)
- But detection then depends on analysis technique
- Behaves more like: 1e35 erg/s / kpc^2



Linden et al, PRD 96, 103016 (2017)



Candidate targets in the Southern Sky?

- Search ATNF pulsar catalogue for pulsars with suitable properties:
  → no TeV association yet, not considered as a candidate
  → 1e34 erg/s < Edot
  → distance < 2 kpc
  → 20 kyr < age
  → age < 1000 kyr

Pulsar	(l,b)	Edot (erg/s)	Age (kyr)	Dist. (kpc)	2FGL source?
J1429-5911	(315.26, 1.30)	7.7e35	60	1.96	Y
J1044-5737	(286.57, 1.16)	8.0e35	40	1.90	Y
J0954-5430	(279.00, -0.10)	1.6e34	171	0.43	N
J0940-5428	(277.51, -1.29)	1.9e36	42	0.38	N
J1057-5226	(285.98, 6.65)	3.0e34	535	0.35	Y
J0905-5127	(271.63, -2.85)	2.4e34	221	1.33	N
J0908-4913	(270.27, -1.02)	4.9e35	112	1.00	N
J1549-4848	(330.49, 4.30)	2.3e34	324	1.31	N
J1731-4744	(342.57, -7.67)	1.1e34	80	0.70	N
J1732-3131	(356.31, 1.01)	1.5e35	111	0.64	Y
J1740-3015	(358.29, 0.24)	8.2e34	21	0.4	N
J1809-2332	(7.39, -2.00)	4.3e35	67	0.88	Y
J1846+0919	(40.69, 5.34)	3.4e34	360	1.53	Y
J1740+1000	(34.01, 20.27)	2.3e35	114	1.23	N

Outlook

- Detecting large, extended sources with IACTs is challenging, but possible
- Good IACT angular resolution – investigate sub-structure and morphology
- H.E.S.S. has made detailed studies of several PWNe to date, and can help resolve hybrid / transitional systems
- IACT field-of-view limits ability to measure size of extended sources
- Observation and analysis strategies need to be carefully considered
- Many potential sources in the Southern sky available to H.E.S.S.

Thank you for your attention

Any Questions?